Higgs Physics at Linear Colliders

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LINE DRIVE A Fermilab Series of Linear Collider Double-Headers

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thanks to . . .

Sławek Tkaczyk, Paul Derwent, Bogdan Dobrescu,
Heather Logan, Konstantin Matchev, Adam Para,
Dave Rainwater, William Wester, Rick Van Kooten,
G.P. Yeh, Sekhar Chivukula, & Chris Quigg

Outline

1. Who let the Higgs out?
2. Properties of the one-doublet model
3. Scalar field theories break down
4. Other models and the decoupling limit
5. SM Higgs measurements at LC
   (a) light 115 GeV $< m_H < 2m_W$
   (b) intermediate $2m_W < m_H < 2m_t$
   (c) heavy $m_H > 2m_t$
6. Comparison with LHC
7. Strategic questions
8. American LC Study

Standard "Model"

Gauge fields:

$$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_Q$$

Chiral fermion fields $(\Im, T, Y)$:

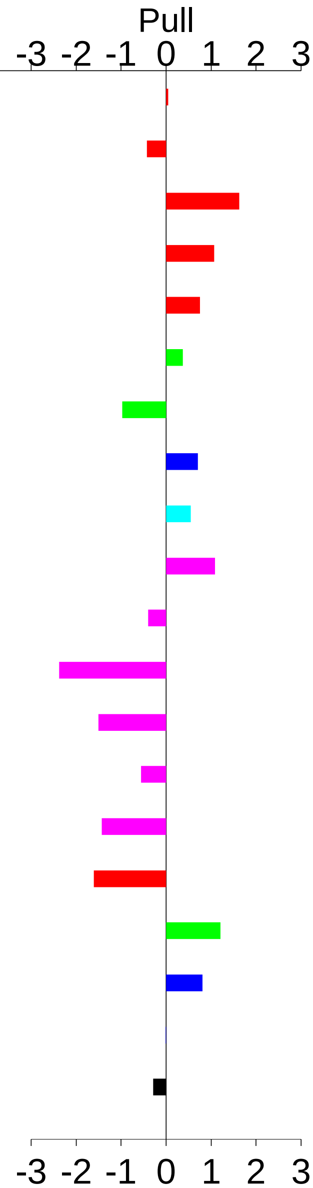
$\bigoplus_{i=1}^{3}(3, \frac{1}{2}, \frac{1}{6})$	left-handed quarks
$\bigoplus_{i=1}^{3}(3, 0, -\frac{1}{3})$	right-handed down-type quarks
$\bigoplus_{i=1}^{3}(3, 0, \frac{2}{3})$	right-handed up-type quarks
$\bigoplus_{i=1}^{3}(1, \frac{1}{2}, -\frac{1}{2})$	left-handed leptons
$\bigoplus_{i=1}^{3}(1, 0, -1)$	right-handed charged leptons

$$T_3 + Y = Q$$

These glyphs summarize laws of Nature.

Osaka 2000

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.07
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.75
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.70
m_W [GeV]	80.427 ± 0.046	.55
R_b	0.21653 ± 0.00069	1.09
R_c	0.1709 ± 0.0034	-.40
$A^{0,b}_{fb}$	0.0990 ± 0.0020	-2.38
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.51
A_b	0.922 ± 0.023	-.55
A_c	0.631 ± 0.026	-1.43
$\sin^2\theta^{lept}_{eff}$	0.23098 ± 0.00026	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.81
m_t [GeV]	174.3 ± 5.1	-.01
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.29



LEP's predecessors (and contemporaries) discovered the known particles, but LEP verified it beyond reproach.

Ask 't Hooft and Veltman.

Standard *Model*

The most economical way to model electroweak symmetry breaking is to add a scalar field

$$(1, \tfrac{1}{2}, \tfrac{1}{2}) \quad \text{Higgs doublet}$$

By gauge symmetry, Higgs can (and does) interact with gauge bosons and matter fields.

Higgs self-interactions lead to

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \qquad \begin{aligned} v &= (\sqrt{2}G_F)^{-1/2} \\ &= 246 \text{ GeV}, \end{aligned}$$

and fluctuations around $\langle\phi\rangle$ are

$$\phi(x) = e^{i\xi^a(x)\tau_a/2v} \begin{pmatrix} 0 \\ [v + H(x)]/\sqrt{2} \end{pmatrix}.$$

Particles produced by $\xi^a(x)$ are the longitudinal W and Z bosons—established beyond doubt.

Particles produced by $H(x)$ are called Higgs bosons.

Higgs, Mass, and Flavor

Interactions with ϕ generate masses:

$$\begin{aligned}
m_{W^\pm}^2 &= \tfrac{1}{4}g_2^2 v^2, \\
m_{Z^0}^2 &= \tfrac{1}{4}(g_1^2 + g_2^2)v^2, \\
m_\ell &= y_\ell v/\sqrt{2}, \\
m_q &= \text{eigenvalue}(y_Q)v/\sqrt{2}, \\
m_H^2 &= 2\lambda v^2.
\end{aligned}$$

For quarks, the misalignment of the up- and down-type quarks' eigenvector matrice yields the CKM matrix and, thus, CP violation.

This meager information is also consistent with models with more Higgs bosons, or with no Higgs boson (*i.e.*, H so massive and wide that for practical purposes it does not exist).

Because the Higgs sector is embedded in flavor physics, its true nature is central to our field.

Scalar Field Theory

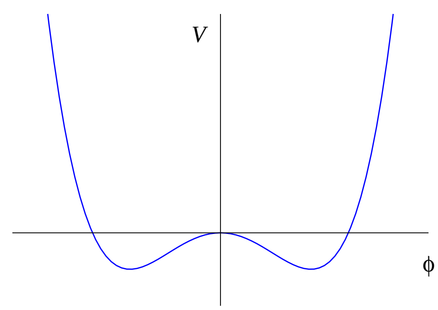
The standard Higgs sector breaks down at some scale, called here Λ_{SM}.

There are aesthetic grounds, from unification of gauge forces and gravity. Experiments could have, but have not, discouraged this notion.

Another argument comes from studying the high-energy behavior of scalar field theories.

The Higgs potential has a parameter $\mu^2 < 0$ that is very sensitive to high energies

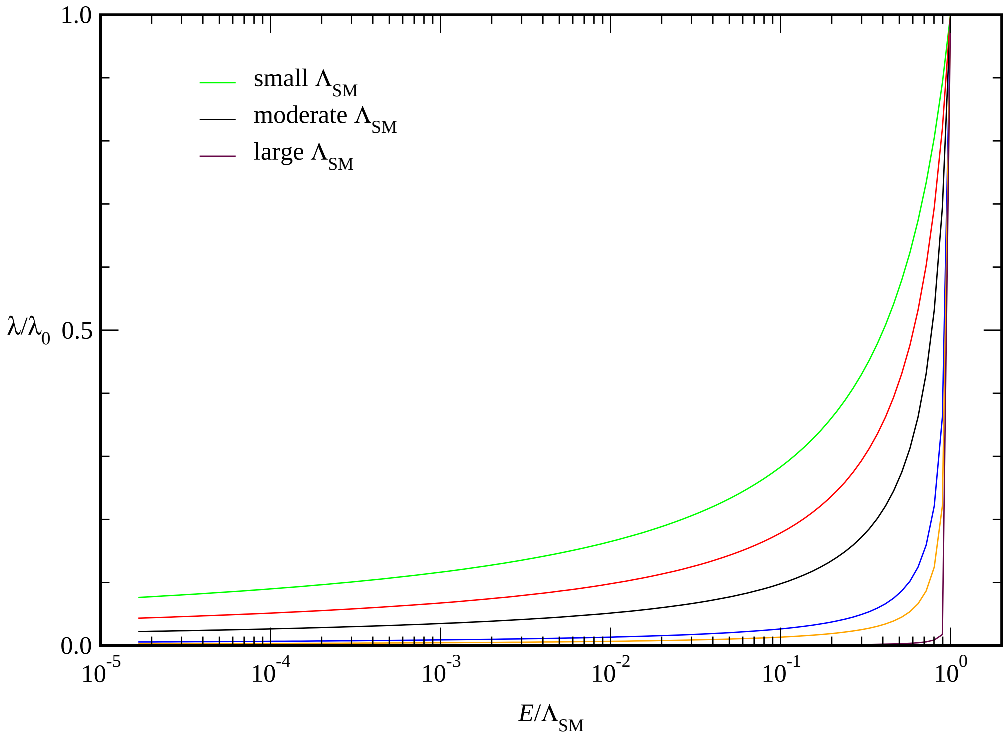
$$\mu^2 = \mu_0^2 + c\Lambda_{\mathrm{SM}}^2 \sum_i (\pm)_i g_i^2,$$



$$\mu^2 = -\lambda v^2$$

If Λ_{SM} is Λ_{GUT} or M_{Planck}, these quadratic divergences pose an extremely serious fine-tuning problem.

The self-coupling grows with energy:



Perturbation theory certainly breaks down at high energy.

Could non-perturbative effects solve the UV problems?

Extensive non-perturbative study concludes that $\Lambda_{SM} \to \infty$ implies $\lambda = 0$ for $E < \Lambda_{SM}$.

But, as long as $\Lambda_{SM} < \infty$, the standard Higgs gives a perfectly viable effective field theory.

New Physics at Λ_{SM}

- New forces? $\Lambda_{\text{SM}} = \Lambda_{\text{TC}}$
  - confining gauge theories (technicolor)
  - massive gauge theories (*e.g.*, topcolor)

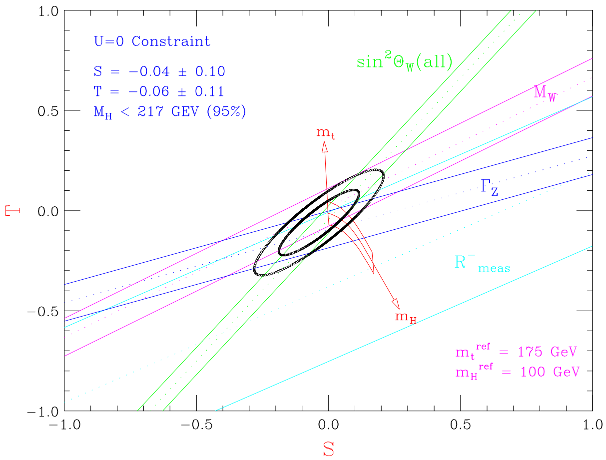
- Supersymmetry? $\Lambda_{\text{SM}} = \tilde{M}$
  - minimal field content (MSSM)
  - non-minimal field content (NMSSMs)

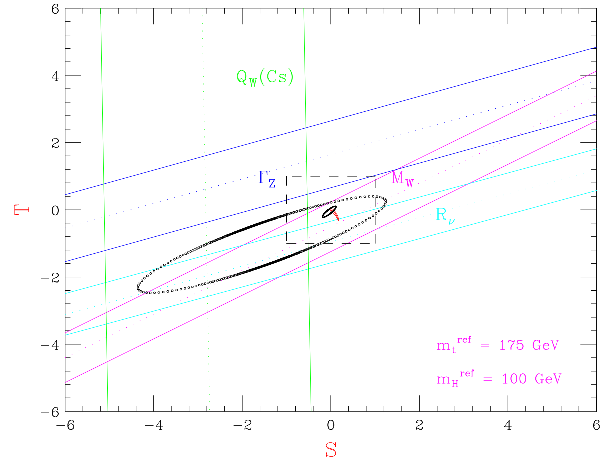
- Extra dimensions? $\Lambda_{\text{SM}} = R^{-1},\ M^*_{\text{Planck}}$
  - large (1 mm)
  - TeV-scale (for some or all SM fields)
  - warped

Combinations are possible.

Viable Models

Which models agree with the precisely measured electroweak observables?





Remarkably, the standard model (with Λ_{SM} arbitrarily high) agrees.

Therefore, any model with a "decoupling limit" automatically agrees too.

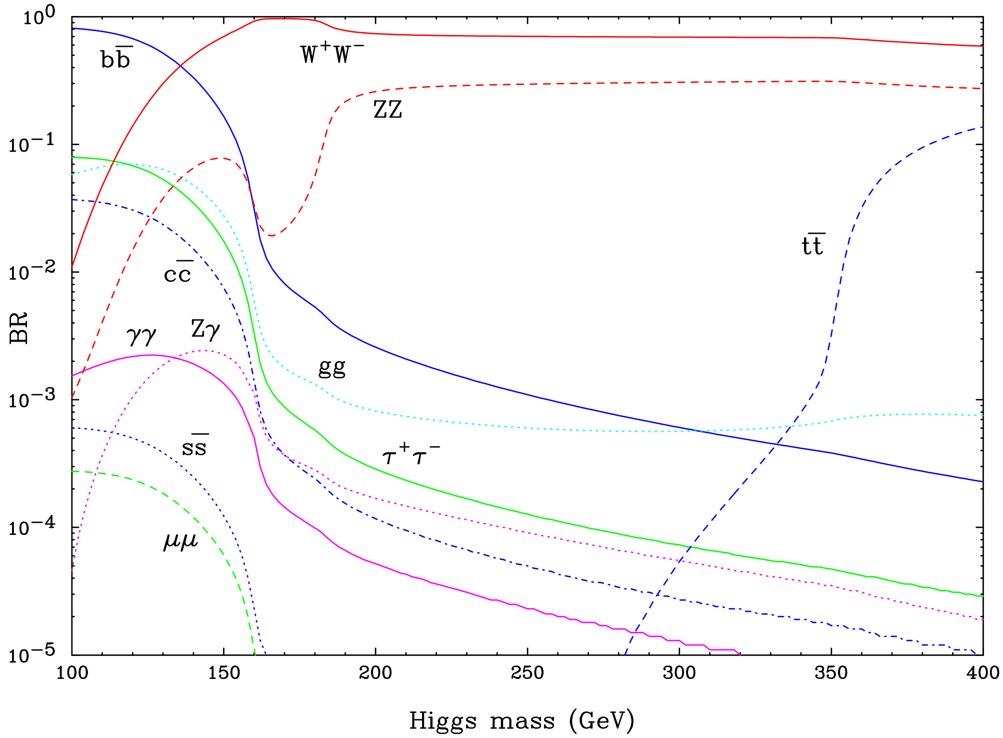
plots $\hookrightarrow$

This includes supersymmetry, extra dimensions, composite models with short-range gauge forces (top seesaw, CDH). A counter-example is technicolor.

Standard Higgs

The neighborhood of the decoupling limit is a good starting point for Higgs studies at LC.

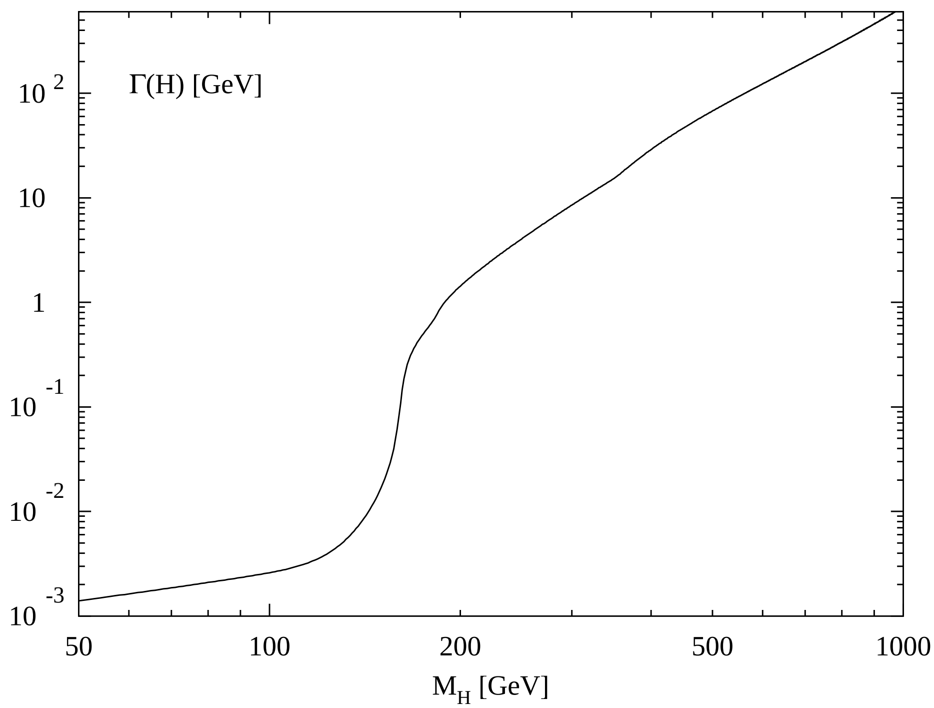
It doesn't lead to a complete survey, but it is representative of good and bad scenarios.



Clearly the properties of the nearly-standard Higgs are sensitive to m_H.

In particular, it matters whether $m_H < 2m_W$.

In the standard model the width of the Higgs depends on m_H.

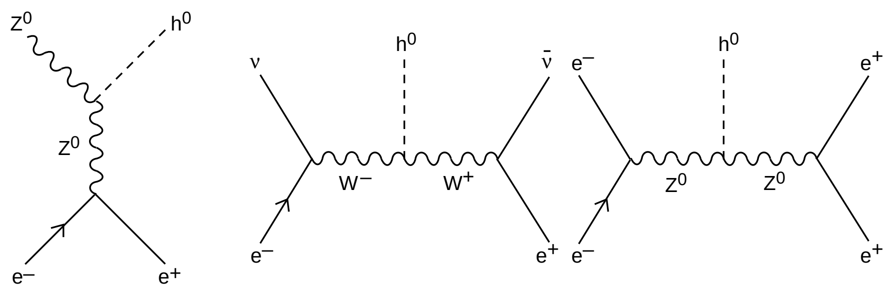


For $m_H < 200$ GeV the width is less than LC detector resolution, but indirect methods are available.

For $m_H > 200$ GeV it can be resolved from the lineshape, at LHC and LC.

Standard Higgs at LC

In e^+e^- collisions the main production mechanisims are Higgsstrahlung (ZH) and vector-boson fusion ($\bar{\nu}H\nu$ and e^+He^-).



Higgsstrahlung is a particularly nice process if the Higgs is non-standard.

The Z gives a trigger and the missing mass spectrum is a model-independent bump finder.

Also powerful if a nearly-standard H decays to non-standard particles, *e.g.*, $h \to AA$ in NMSSM or certain composite models.

Fusion processes are helpful when running at $\sqrt{s_{\mathrm{max}}}$ or for strong WW scattering.

Light Higgs at LC

There are two indications that a nearly-standard Higgs is light ($m_H < 2m_W$):

- precisely measured electroweak observables
- direct evidence at LEP ($< 3\sigma$)

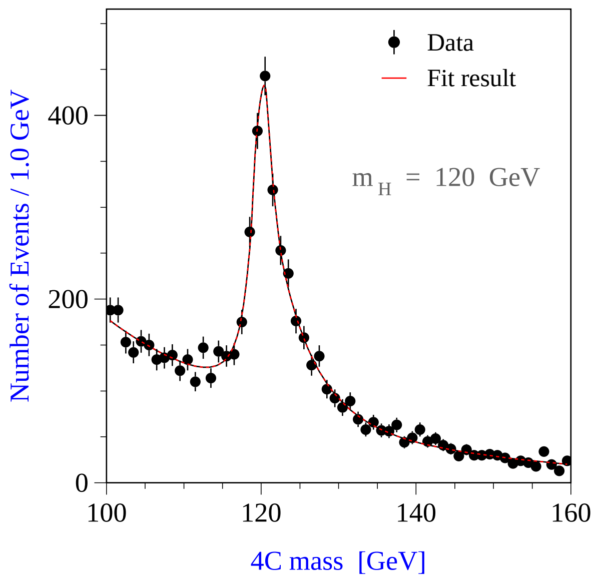
For the first reason, because susy prefers light Higgs, and because it is the most interesting, the light Higgs is the most studied.

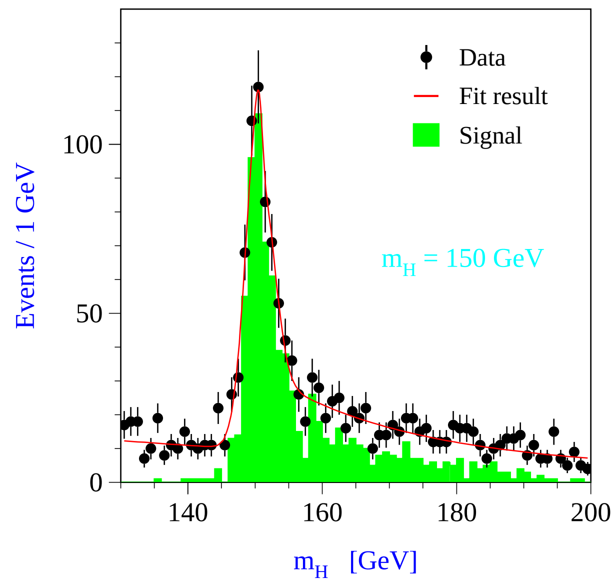
Well summarized at LCWS2000 by Battaglia and Desch, `hep-ph/0101165`. For the light Higgs, all the SM properties can be tested.

In particular, one can test whether the particle discovered at the LHC is a scalar, and whether it gives mass to W and Z, charged leptons, down-type quarks, and up-type quarks.

N.B. 50,000–60,000 Higgs events for 500 fb^{-1}.

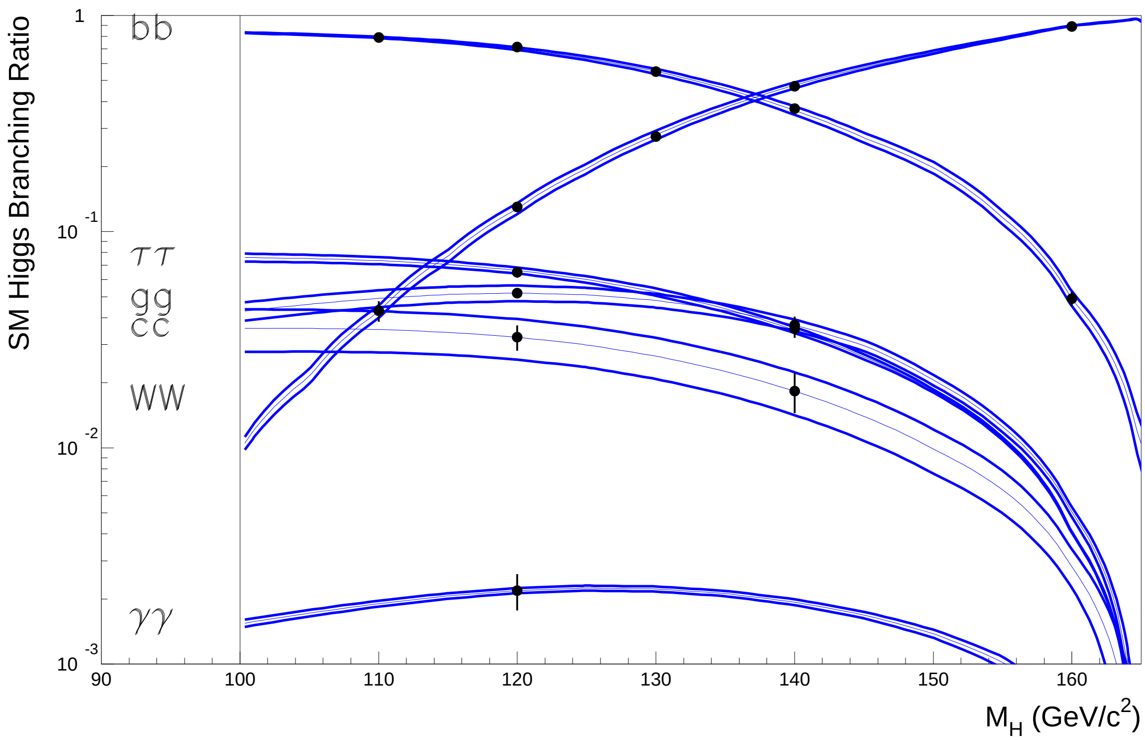
Mass: 40 MeV $< \delta m_H <$ 90 MeV, i.e. $<$ 0.06%.





Presumably, this kind of precision will turn out to be welcome.

The J^{PC} can be looked at three ways: $H \to \gamma\gamma$ or ZZ; rise of σ_{HZ} at threshold; and angular distributions. CP admixtures are hard: s-channel $\gamma\gamma \to H$ may be the right path.

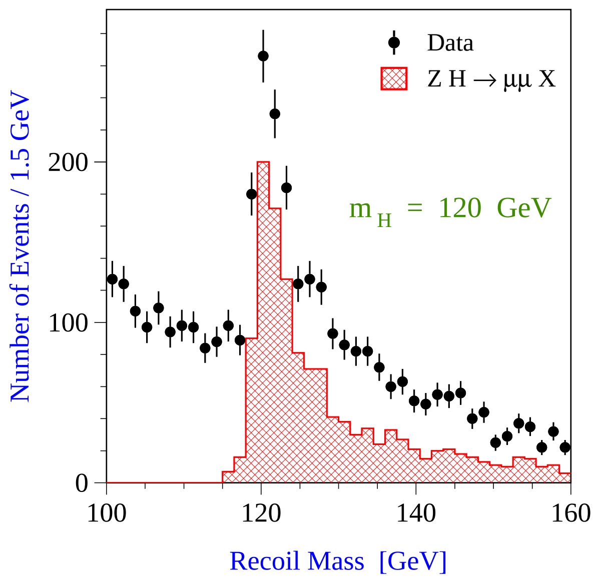


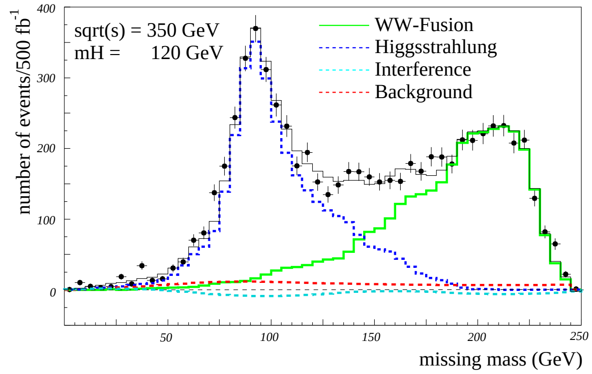
The couplings to fermions (and gluons and photons) are obtained by measuring the branching ratios of Higgs decays.

$f\bar{f} \backslash \quad m_H$:	120 GeV	140 GeV	160 GeV
$b\bar{b}$	0.024	0.026	0.065
$c\bar{c}$	0.085	0.190	—
$\tau^+\tau^-$	0.050	0.080	—
gg	0.055	0.140	—

Relative accuracy in the determination of Higgs boson decay branching ratios for 500 fb^{-1} at $\sqrt{s} = 350$ GeV.

The coupling to top can be measured (to several %) from $t\bar{t}H$ events at 0.8–1.0 TeV.





The couplings to W and Z are obtained by measuring the production cross section and the branching ratios.

σ, BR $\setminus m_H$	120 GeV	140 GeV	160 GeV
$\sigma(HZ)$	0.024	0.027	0.030
$\sigma(\bar{\nu}_e H \nu_e)$	0.028	0.037	0.130
BR(WW^*)	0.051	0.025	0.021

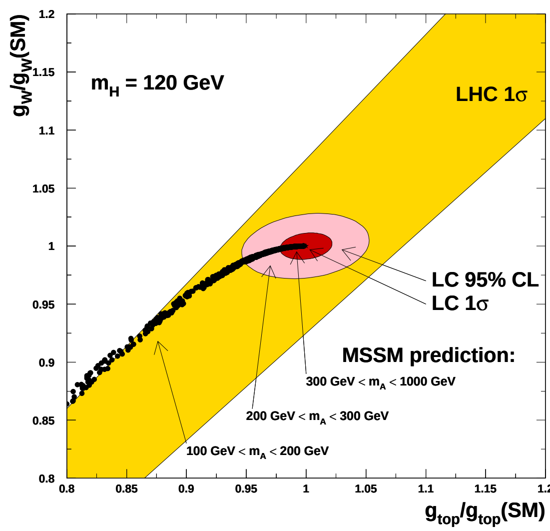
Relative accuracy on the determination of the Higgs production cross sections and branching ratios in gauge bosons for 500 fb^{-1} of LC data at $\sqrt{s} = 350$ or 500 GeV.

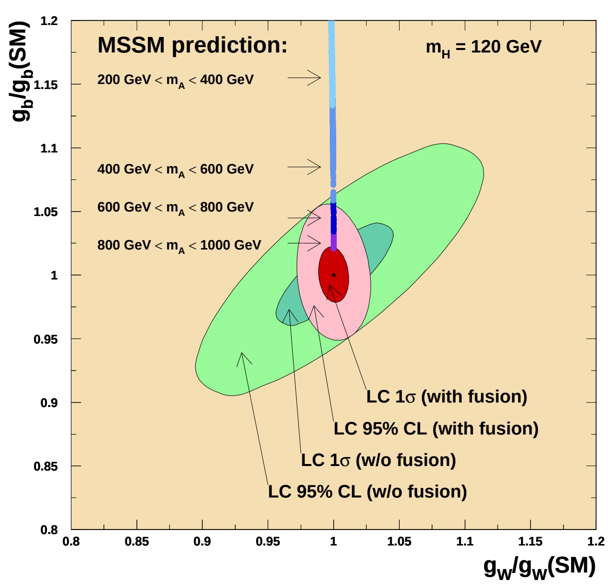
An excellent by-product is the width, model-independently, $\Gamma = \Gamma_{WW}/\mathrm{BR}_{WW}$ to 6–13%.

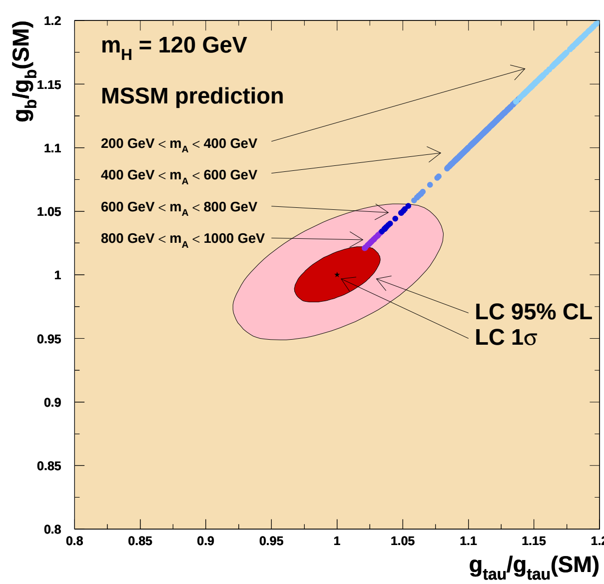
By checking whether BR $\propto m^2$ one can check whether H generates the other masses.

The model-independently width checks whether there are non-standard decays.

The precision allows one to probe indirectly for higher-mass states, for example the CP-odd A of the MSSM.







To test the Higgs mechanism, one must also measure the shape of the Higgs potential.

Is it a sombrero?

The cross section for double (triple) Higgs production is sensitive to the triple (quartic) Higgs coupling. They should be related to

$$\begin{aligned} g_{HHH} &= \lambda v \\ g_{HHHH} &= \tfrac{1}{4}\lambda \end{aligned}$$

The cross section for triple Higgs production appears to be too small to get g_{HHHH}.

With high integrated luminosity it should be possible to extract g_{HHH} from σ_{ZHH} and $\sigma_{\bar{\nu}HH\nu}$. For example, for $m_H = 120$ GeV at $\sqrt{s} = 500$ GeV,

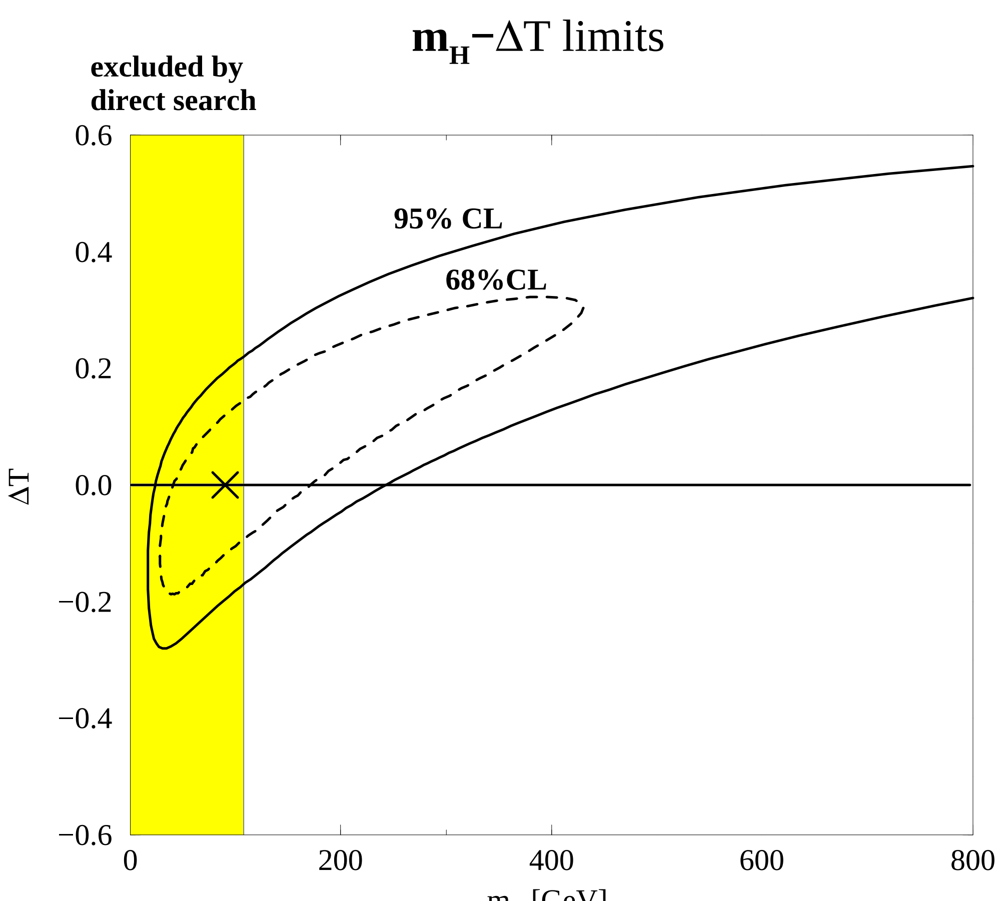
$$\delta g_{HHH}/g_{HHH} \sim 23\%$$

with 1000 fb^{-1} [Castanier, Gay, Lutz, and Orloff hep-ex/0101028].

Intermediate Mass

The light Higgs program is, alas, not guaranteed.

Unless Λ_{SM} is unnaturally large, massive (TeV) particles could compensate the Higgs' contribution to S and T.



Chivukula, Hölbling, Evans, hep-ph/0002022

There is no shortage of examples:

- add to SM a vector-like quark
- allow gauge fields to propagate in extra dimensions
- allow warped a extra dimension

In each case the precision EW data permit a nearly-standard Higgs with m_H up to several hundred GeV.

Even in (non-minimal) susy a mass of 200 GeV is (theoretically) allowed.

The key question is whether $m_H < 2m_W + \varepsilon$, after which the decays to $f\bar{f}$ become rare or very rare. (For $m_H > 2m_t$ the BR to $t\bar{t}$ is large enough to measure [Wester].)

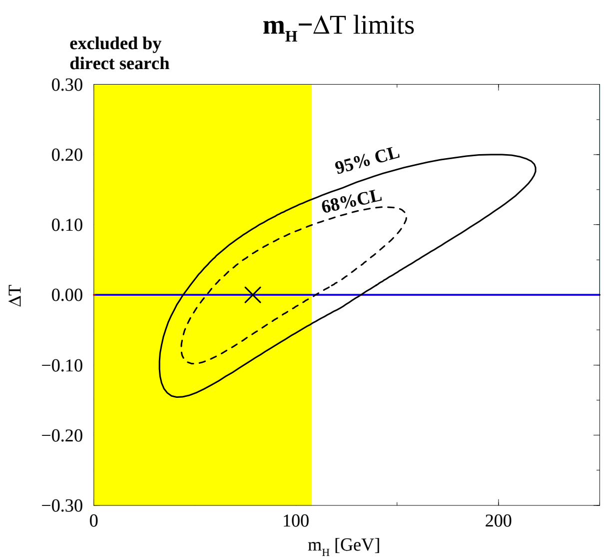
A first study, using ZH events and $Z \to \ell^+\ell^-$, shows that the statistical error on BR($b\bar{b}$) remains below 30%, for $m_H < 200$ GeV, but 2000 fb^{-1} would be needed [Derwent].

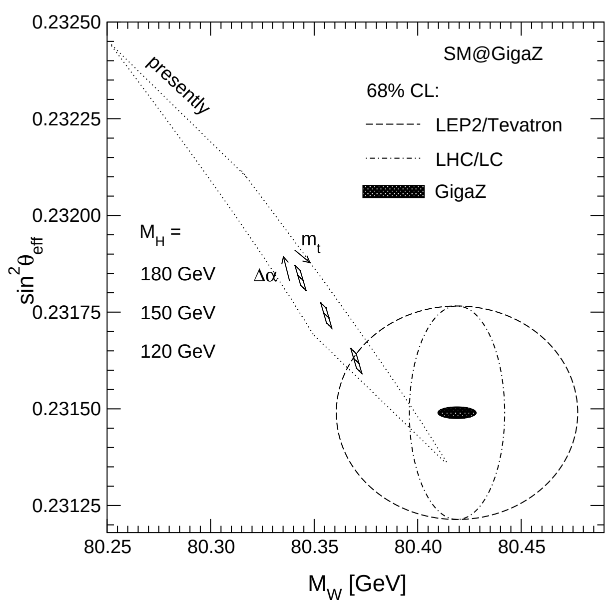
Heavy Higgs and Giga$Z$

If the Higgs mass is such that the fermion couplings are to small to measure, the LC Higgs loses much of its zing.

It still measures the W and Z couplings to a greater precision than the LHC. The precision is good for checking whether the observed H is fully reponsible for m_W and m_Z.

The LC will have the flexibility to run at the Z^0 resonance, producing 10^8–10^9 Z bosons, and the WW threshold, reducing δm_W to 6 MeV.





Comparison with LHC

The comparison with LHC has quantitative and qualitative aspects.

The LHC will almost certainly discover the Higgs. The LC is for elucidation.

If the Higgs is light, then the LC does a complete job of measuring the couplings of the Higgs to standard and non-standard matter, and itself.

If not, there is less to do, but the Giga$Z$ option is useful for sorting out “what went wrong”.

$\boxed{\text{Reasons for LC}}$

Model-independent, qualitative reasons

- SM Higgs is effective FT for $E < \Lambda_{\text{SM}}$
- $\Lambda_{\text{SM}} < \infty$
- most natural $\Lambda_{\text{SM}} \approx \mu \approx 1$ TeV ($\stackrel{\times}{\div}\sqrt{10}$)
- will need $\ell^+\ell^-$ collisions to draw connection between physics at Λ_{SM} and EWSB

Not precise, but accurate.

Reasons for LC

Model-dependent, quantitative reasons

- if 115 GeV $< m_H < 2m_W + \varepsilon$, then can show that H gives mass to gauge bosons (W and Z), charged leptons (τ), up-type quarks (c and t), down-type quarks (b), and H itself.

- if $2m_{\tilde{\chi}} < \sqrt{s}$, then $\delta m_{\tilde{\chi}} \sim 100$ MeV

- if $m_Z + m_H + \Gamma_H < \sqrt{s}$, then can trace out line shape

- if $m_Z + m_H < \sqrt{s} + \Gamma_H$, then can see rising edge

- if $2m_A < m_H$, then ?

Precise, but need not be accurate.

Which LC?

1. High luminosity. For Higgs, high precision is essential. In likely scenarios, many other measurements are needed too.

2. Polarization. At the electroweak scale and above, left- and right-handed fermions are fundamentally different.

3. Flexibility. In some scenarios the Giga$Z$ option is not merely interesting, but valuable for pointing to accelerators beyond LHC and the 1 TeV LC.

4. Upgradability. The TeV scale does not stop at $\sqrt{s} = 1$ TeV. It would be useful to understand what, of the competing 1 TeV designs, could be reused for a multi-TeV LC.

American LC Study

Charlie Baltay and Paul Grannis

Higgs boson(s)	Rick Van Kooten, Howie Haber, ASK
Susy sparticles	F. Paige, J. Feng, U. Nauenberg, J. Wells
Alternative NP	Sławek Tkaczyk, JoAnne Hewett
Strong EWSB	Tim Barklow, Bogdan Dobrescu
Electroweak	Bill Marciano
Top quark	David Gerdes, Uli Baur
QCD	Bruce Schumm, Lynne Orr
$\gamma\gamma$, $e\gamma$, e^-e^-	Karl van Bibber, Clem Heusch, J. Feng
Simulation	Norman Graf, Adam Para, Michael Peskin
Vertex detectors	Jim Brau
Tracking	Keith Riles, John Jaros
Particle ID	Hitoshi Yamamoto, Robert Wilson
Calorimetry	Ray Frey, Frank Porter, Andre Turcot
Muon detectors	David Koltick, Gene Fisk
DAQ, etc	Tony Barker, Marty Breidenbach
Interaction region	Tom Markiewicz, Stan Hertzbach

http://lcwws.physics.yale.edu/lc/america.html

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Some possibilities:

- Measurement of BR($H \to b\bar{b}$) for $m_H > 2m_W$. Paul Derwent has done a first pass at this, using only HZ events and then only leptonic Z decays. How well, as function of m_H can one do, when neutrino and hadronic Z decays are added? When $\bar{\nu}H\nu$ production is included?

- Distinguishing SM and MSSM Higgs BRs (for light Higgs). Marcela Carena and Heather Logan are looking into the MSSM with CP violation.

- Further simulations of spin determination. Adam Para has done work for Higgs and intends to refine it. Superpartners' spins?

- $h/H \to AA$ decay in non-M SSM and in certain composite models. See hep-ph/0005308 [Dobrescu, Landsberg, Matchev].

- Search for maximal weirdness. Theorists are coming up with new ideas every day. Talk to Joe Lykken or Martin Schmaltz.